

# **The role of building performance simulation in the design of ECHO, Team Ontario's entry to the U.S. Department of Energy Solar Decathlon 2013**

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## **Abstract**

The U.S. Department of Energy Solar Decathlon is a biennial sustainable design competition that challenges 20 collegiate teams to design, build, and operate net-zero energy houses. Team Ontario, comprised of students and faculty from Queen's University, Carleton University, and Algonquin College, recently competed in the 2013 competition in Irvine, California with their house, ECHO – an ECological HOme for the next generation of young homeowners. This paper describes how the building performance simulation work played a crucial role in the integrated design process. Building models were initially created in EnergyPlus and then in TRNSYS to couple it to the mechanical system model, a solar-assisted heat pump with two storage tanks. Annual building loads in Ottawa, Ontario and during the 8-day competition in Irvine were estimated and compared to actual competition performance. Although heating loads dominate in typical Canadian residential buildings, the simulation results suggest that the annual heating and cooling loads were approximately equal. This result is attributed to high levels of insulation and effective control of solar gains in the winter. Simulation results suggest that ECHO requires about 25% of the energy of a typical Canadian home (34% when scaling space conditioning and lighting loads by size).

## **1 Introduction**

The U.S. Department of Energy Solar Decathlon is a biennial competition that challenges 20 collegiate teams from the United States and around the world to design, build, and operate net-positive energy, solar-powered houses with a maximum conditioned floor area of 93 m<sup>2</sup> (1000 ft<sup>2</sup>). The teams are selected through a competitive bidding process and are required to raise most of the funding through sponsorships. Each team's 'competition prototype' house is designed for a specific climate and is typically first constructed locally, before being disassembled and shipped to the competition site by truck, rail, or boat. Each team has 8 days to assemble their house at the site, run a public exhibit including professional jury walk-throughs, and then disassemble the house in 5 days.

The three goals of the Solar Decathlon include educating students and the public about green products and design solutions, demonstrating the comfort and affordability of high-performance housing, and providing students with training in applied sustainability (U.S. Department of Energy 2013). Each competition prototype is judged across 10 contests, half of which are measured and half of which are judged by professional juries, as per Table 1.

**Table 1: Solar Decathlon contests**

Measured	Juried
Energy Balance	Engineering
Appliances	Architecture
Home Entertainment	Communications
Comfort Zone	Affordability
Hot Water	Market Appeal

Each contest is worth a maximum of 100 points; the winning team has the highest aggregate score. Further details on the results of the 2013 competition can be found at [www.solardecathlon.gov](http://www.solardecathlon.gov).

Team Ontario was an interdisciplinary team of students and faculty from Queen's University, Carleton University, and Algonquin College. In November 2011, the team successfully submitted a proposal to the U.S. Department of Energy for the 2013 competition. The team spent the next year and a half designing and constructing ECHO – an ECological HOME for the next generation of young homeowners.

This paper describes how building performance simulation (BPS) played an integral role in the design of ECHO. The paper begins with a brief discussion of how the work contributed to removing barriers to the application of BPS in design practice. This is followed by the methodology of the simulation exercise and examples of sensitivity studies. Simulation results are then presented along with a comparison to actual performance during the competition. The paper concludes with some recommendations for further work utilizing ECHO as a platform for student learning of BPS tools and methodologies.

## **2 Removing Barriers to Application of Building Simulation in Design Practice**

Team Ontario's approach to integrating BPS addressed the three goals of the Solar Decathlon: education, demonstration, and training. Training or 'capacity building' involved the creation of a dedicated BPS team comprised of three full-time summer student employees, numerous volunteers, and a faculty advisor with significant experience in BPS.

Initial work consisted of learning to use the simulation tools (EnergyPlus and TRNSYS) through teaching models and presentations. Once a level of comfort with the tools was reached, an iterative approach was used to simulate the energy load of early architectural designs of ECHO, with an increasing level of complexity – for example, the first iteration only incorporated simple geometry, with successive iterations adding ventilation, infiltration, internal gains, and other building energy components. By building on preceding iterations, the team learned how each component of the house affected energy performance.

Other members of the team were educated in the benefits of BPS through the integrated design process. In this approach, all disciplines are involved at each stage of the design. This holistic approach is generally accepted as a better process for achieving a high performing building than traditional design approaches (Zimmerman 2006). Early sensitivity studies helped influence design decisions in order to minimize the size of the photovoltaic (PV) array required to generate more energy than is consumed on an annual basis, while still meeting aesthetic and cost criteria.

The integrated design team consisted of students and faculty from civil, mechanical, electrical, and sustainable and renewable energy engineering, architecture, construction trades, interior design, and business disciplines. In total, thirty-two full-time summer student positions were funded across two years, with more than seventy volunteers directly

contributing to the project. Other students were also involved, for example fourth year engineering capstone project teams at Carleton University and Queen's University. Four team members pursuing graduate studies in engineering also made use of BPS tools for their academic work.

Team Ontario had a significant demonstration component with respect to BPS. An estimated 25,000-30,000 people viewed ECHO during the competition, including design and construction industry professionals, students, media, and members of the community with an interest in sustainability. The merits of BPS were featured during this demonstration through signage and oral presentations. This included the relevance of BPS to other aspects of the design, such as an integrated mechanical system (Chu et al. 2013), predictive shading controls (Huchuk et al. 2013), and validation of a high-performance wall assembly utilizing vacuum insulation panels (VIPs) (Schiedel et al. 2013). The role of simulation in achieving a net-positive energy home was effectively demonstrated to visitors and to the professional juries, contributing to the team's first-place finish in the Engineering Contest.

### **3 Building Performance Simulation Methodology, Results, and Discussion**

Building performance simulation exercises were primarily conducted in EnergyPlus (U.S. Department of Energy 2012). Advantages of this program include a well-documented and supported interface, significant user base, and extensive validation testing (U.S. Department of Energy 2011). The software is also freely distributed, which is an asset for a student volunteer network with limited funding. Disadvantages include a steeper learning curve than some other programs and potential limitations when modeling atypical mechanical systems. The objectives of the BPS were to:

- Analyze annual space heating and cooling loads based on an Ottawa, Ontario climate;
- Provide feedback to the integrated design team on the energy impact of design options;
- Conduct solar photovoltaic (PV) energy simulations; and,
- Ensure electrical energy requirements were less than PV output for a year in Ottawa and for the eight days of the Energy Balance contest during the competition in Irvine, California.

One typical approach to building simulation, such as the Leadership in Energy and Environmental Design (LEED) building rating system, is to construct a 'reference' building based on the National Building Code or ASHRAE 189.2 standards (CaGBC 2009). This was not done for two reasons. First, the design of ECHO was subject to a number of constraints, including:

- No combustion allowed for heat or electricity generation, as specified by the competition organizers;
- The decision to use VIPs in the building envelope design for research purposes;
- A rectangular-shaped structure with a flat roof to facilitate shipping by truck; and,
- An 'exostructure' on the southern exterior that provided an angled mount for solar PV panels and passive shading during the summer.

The second reason a reference model was not developed is that the merits of the reference building approach were not fully appreciated by the building simulation team. In retrospect, it would have been more beneficial to generate the reference model and then conduct the sensitivity studies; this approach is more consistent across projects and supports more relevant comparative analysis. As a result, the 'base model' of ECHO compared to typical high performance building analyses more closely resembles the refined (final) design.

Table 2 describes some relevant parameters of the base model simulation that were held constant across the sensitivity studies. The set point temperatures were specified by the

competition organizers, while the conditioned floor area and window areas were determined by the architecture team in conjunction with building simulation results.

**Table 2: Base model parameters**

<b>Parameter</b>	<b>Value</b>
<b>Conditioned area</b>	88 m <sup>2</sup>
<b>Window-wall ratio</b>	
North	11.5%
East	13%
West	13%
South	22%
Total	16%
<b>Heating set point</b>	21°C
<b>Cooling set point</b>	24°C
<b>Number of occupants</b>	2; based on 40-hour/week work schedule
<b>Air ventilation</b>	24 L/s; based on ASHRAE 62.2 (ASHRAE 2007)

Plug loads in the model were based on indicative values from a literature review (Hendron et al. 2004 and Knight et al. 2007). Values for calculating electrical energy requirements were later updated with ‘as-built’ specifications, which used EnergyStar® (Natural Resources Canada 2013) guidelines to choose energy efficient appliances.

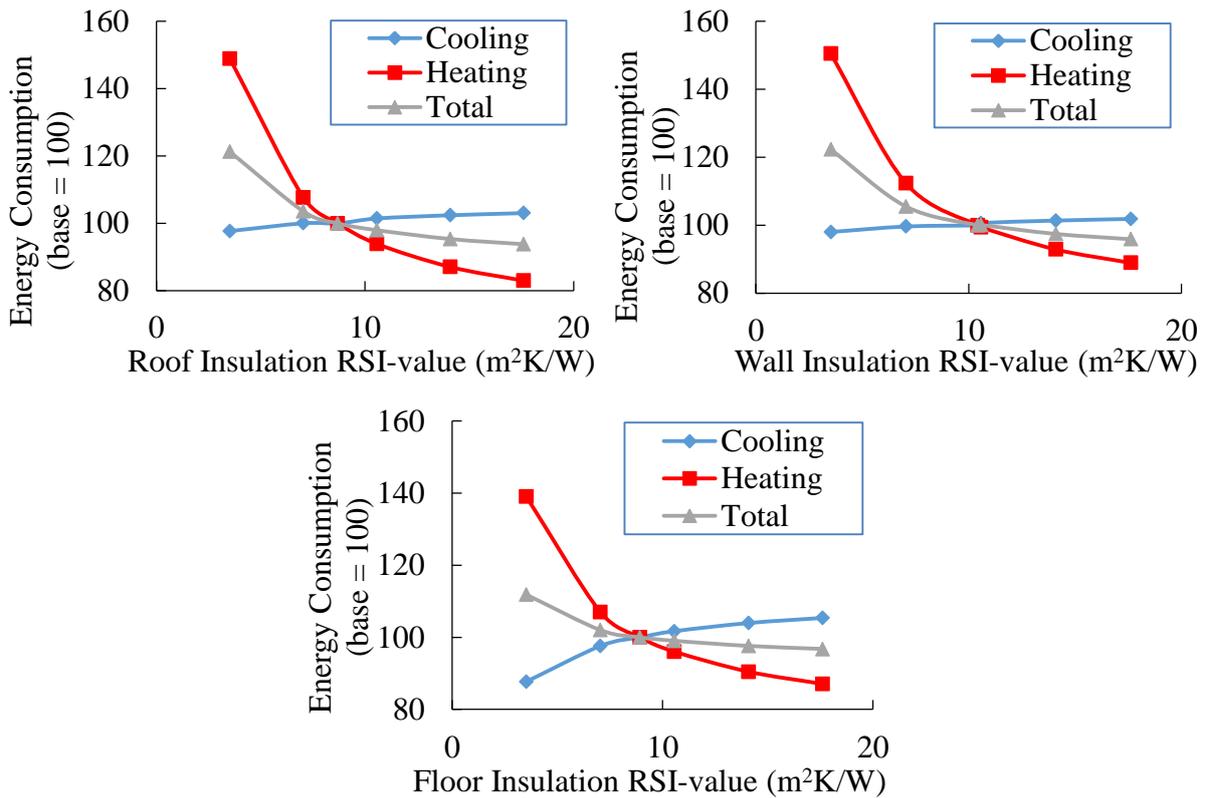
Sensitivity studies were conducted by choosing several values for each parameter and running a simulation while holding all other values constant. Results were normalized to the base model space heating, space cooling, and total space conditioning loads on an annual basis in Ottawa. A 15-minute time step was chosen and the Ottawa Typical Meteorological Year 2 (TMY2) file used for weather inputs.

### ***Sensitivity Results and Discussion***

Figure 1 - Figure 3 shows the result of selected sensitivity studies. It is interesting to note that, while the heating load of a typical Canadian house is an order of magnitude higher than the cooling load, ECHO’s heating and cooling loads are approximately equal.

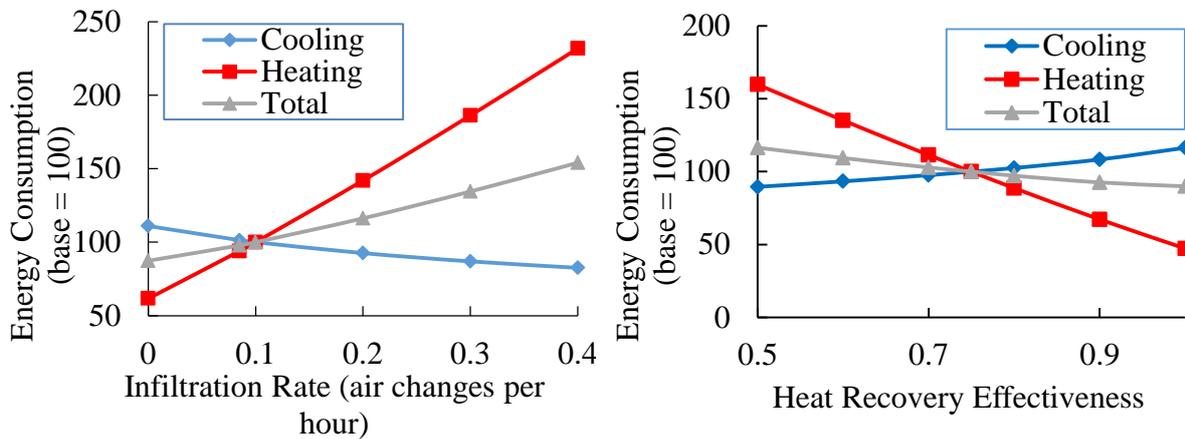
The impact of varying the insulation level in the roof, walls, and floor is shown in Figure 1. A high thermal insulation level was chosen for the base model in recognition of the requirement to utilize VIPs, which are excellent thermal insulators. This technology has been utilized in appliances such as refrigerators, but has seen little deployment in the built environment. Use of this technology provided an opportunity to advance the research into modeling, wall design, and practical aspects relating to construction.

Diminishing returns to greater thermal insulation were noted around RSI-8 – RSI-10 m<sup>2</sup>K/W. Thus it was decided to strive for a thermal resistance in that range.



**Figure 1: Insulation level sensitivity study results**

Figure 2 shows the impact of air exchange, through air infiltration (inadvertent, through cracks in the building envelope) and ventilation through mechanical means (to provide acceptable indoor air quality). The mechanical ventilation used a heat recovery ventilator (HRV) to pre-heat incoming outdoor air.



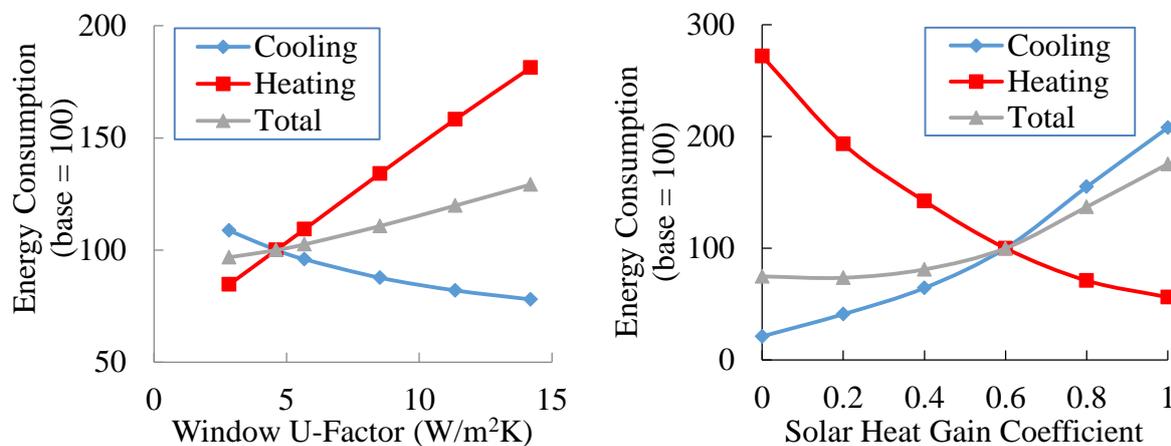
**Figure 2: Air infiltration and ventilation heat recovery effectiveness sensitivity study results**

Recognizing the importance of air-tight construction in Canadian housing, the base model assumes a very tight envelope, 0.085 air changes per hour (ACH). The air infiltration study quantified the impacts of leaks on overall energy consumption, and reinforced the need for the envelope design and construction teams to pay careful attention to air tightness. This effort was successful; a blower-door test following construction indicated 1.4 air changes per

hour at 50 Pa pressure difference. Using the ‘divide by 20’ rule of thumb (Sherman 1995) this corresponds to about 0.07 ACH ‘natural’ infiltration.

Figure 2 also shows how changing the heat recovery effectiveness of the HRV affects building loads. The heating load improves linearly. The cooling load has a negative slope, potentially indicating increased latent cooling or unwanted pre-heating of outdoor air at night during cooling conditions. These results further suggest that the HRV should be seasonally controlled, for example by implementing a bypass mechanism for when outdoor air enthalpy is lower than indoors. Although it was planned to incorporate a bypass mechanism (or ‘outdoor air economizer’) to take advantage of this ‘free cooling’ effect, it was unfortunately not implemented in the final design.

Figure 3 shows the impact of adjusting window properties – the U-Factor or thermal transmittance value, and the solar heat gain coefficient, a dimensionless parameter that reflects the amount of solar energy transmitted through the window. A higher U-Factor results in significantly higher heating energy, implying significant thermal bridging across the windows - an unsurprising result considering the high thermal insulation of the rest of the building envelope.



**Figure 3: Window parameter sensitivity study results**

Although these results suggest a low solar heat gain coefficient is desirable, the simulation was conducted with an earlier building model that did not have shading objects implemented, i.e., windows were unshaded at all times. If ECHO’s predictive shading system or even a reactive shade were implemented in the building model, cooling loads would be significantly decreased; thus it was recommended to select windows with a higher level of solar heat gain in order to minimize heating loads.

Window size and orientation play a significant role in energy consumption. These parameters were not the subject of a specific sensitivity study; rather, modifications suggested by the architecture team were analyzed in an iterative fashion.

Major findings that were considered in the final design of the house include:

- The region of diminishing returns from increasing insulation levels and window U-factor;
- Careful attention to air tightness during construction;
- The importance of ventilation heat recovery. Seasonal control of the HRV was also noted as a good strategy to reduce cooling loads;
- Windows with higher solar heat gain coefficients are effective at reducing heating loads but require careful control to avoid overheating in the summer; and,

- The thermal mass of finishes (e.g., granite countertops or flooring types) had no appreciable impact on loads. Finishes were left to the interior design team without consideration for energy implications.

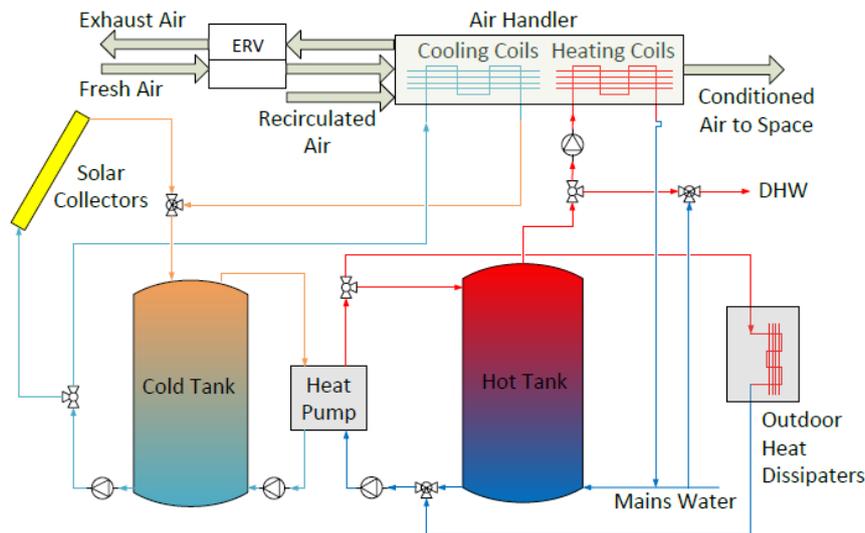
Further investigation is required to update the model to reflect the house as it was built and to compare and validate the model against actual performance.

### ***EnergyPlus and TRNSYS Comparison***

A second building model was developed in TRNSYS 17 using the TRNBuild plug-in (Solar Energy Laboratory 2005). The same parameters as the EnergyPlus model were used to ensure both models reflected, as closely as possible, the design and expected occupancy profile.

This work served two purposes. First, it allowed for comparison to the EnergyPlus results in order to increase confidence in the model output. Second, it supported coupling of the building model with the Integrated Mechanical System (IMS) model, a two-tank, solar-assisted heat pump that provides space heating and cooling, dehumidification, domestic hot water, and fresh air ventilation in a single integrated system.

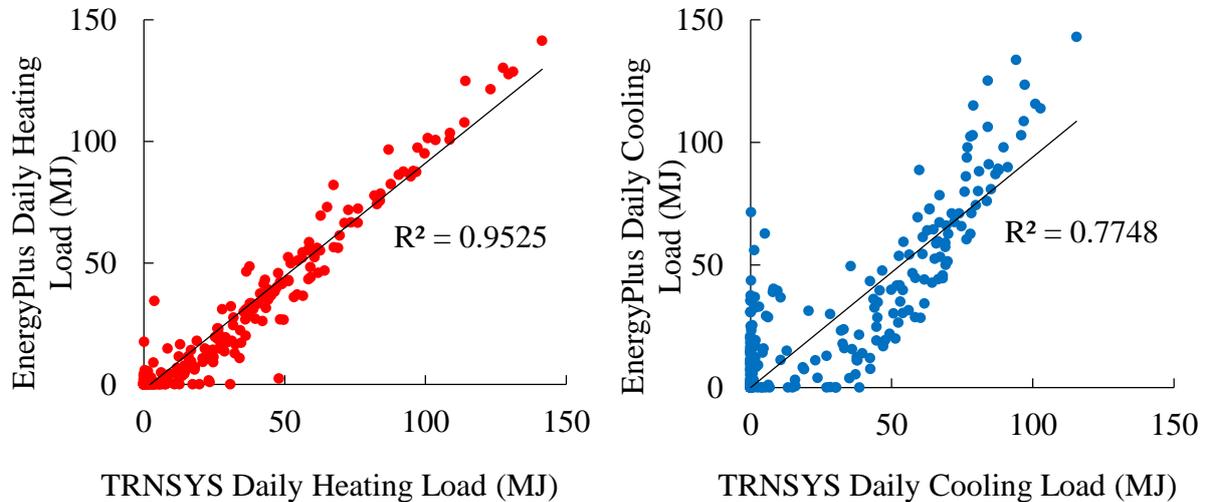
TRNSYS was used to model the IMS, shown schematically in Figure 4; of particular interest was the complex transient operation of the system. A liquid-to-liquid heat pump continually transfers energy from the ‘cold tank’ to the ‘hot tank’. In the summer, the fluid in the cold tank is used for space cooling, while in the winter the cold tank is charged by solar thermal collectors to boost the amount of energy available for the heat pump. The water in the hot tank is used for domestic hot water year-round, and for space heating in the winter. An auxiliary electric heater in the hot tank ensures sufficient energy to meet demand, while an outdoor heat dissipater prevents the hot tank from overheating in the summer. The solar collectors do not operate in cooling mode, as energy recovered from space cooling is used to provide domestic hot water. Further information regarding the IMS model and sensitivity studies of the system can be found in (Chu et al. 2013).



**Figure 4: Integrated mechanical system (adapted from Chu et al. 2013)**

Figure 5 compares the daily ideal heating and cooling loads of the two models. In an ideal system, an energy balance is conducted to precisely meet the heating or cooling load at each time-step – thus the specifics of the mechanical system are not modeled. The purpose of this comparison was to improve confidence in the simulation results.

The heating loads match quite well, while greater scatter occurs in the cooling loads. Larger discrepancies between the models occurred when fixed shading (i.e., the exostructure) and internal gains were implemented. Further investigation is required to identify the sources of the discrepancy. One possibility is differences in the heat transfer model used to determine thermal interaction between the two zones of the house.



**Figure 5. Comparison of daily heating and cooling loads from two software tools**

#### 4 Simulated Annual and Competition Performance

Table 3 summarizes simulated annual heating and cooling loads and rates. The heating load from EnergyPlus was about 1.0 GJ or 14% less than the heating load from TRNSYS while the cooling load was about 0.2 GJ or 2.8% higher than the cooling load from TRNSYS.

When coupled with the IMS model in TRNSYS, loads were significantly higher. This is because the IMS has significant hysteresis effects, due to the thermal storage tanks and utilization of solar thermal energy and heat recovery inputs. These results demonstrate that great care must be taken when interpreting the results of ideal space conditioning loads.

**Table 3: Comparison of TRNSYS and EnergyPlus annual space conditioning loads**

System Type	Simulation Tool	Annual Heating Load (GJ)	Annual Cooling Load (GJ)	Max Heating Rate (kW)	Max Cooling Rate (kW)
Ideal	TRNSYS	7.4	7.2	3.9	2.7
Ideal	EnergyPlus	6.2	7.4	4.4	2.9
Non-ideal (IMS)	TRNSYS	10.5*	12.7*	3.8**	4.4**

\* These loads represent the annual heat transferred through the heating and cooling coils of the IMS. The cooling load includes dehumidification by overcooling air to 10°C and does not include the energy required to reheat to the supply air to 16°C.

\*\*95% of the recorded heating and cooling coil loads were below these values.

Figure 6 compares the simulated annual electricity consumption of ECHO to 2010 energy consumption figures for Ontario (Natural Resources Canada 2012). Note that estimates for ECHO account for the impact of the IMS on reducing loads due to solar thermal storage and heat recovery, i.e., only electrical input is indicated. The space cooling figure accounts only for homes with active space cooling, about 75% of residential floor area in Ontario. Since the average Ontario home is larger than ECHO – 142 m<sup>2</sup> versus 87 m<sup>2</sup> –

figures for space heating and cooling and lighting are scaled, as these parameters tend to correlate closely with floor area; appliance and hot water energy are left unscaled.

On an annual basis, ECHO is predicted to use 34% of the energy of a typical Ontario home, scaled to the floor area as described above. On a per-household basis, the figure is 25%.

The appliance load is based on selection of high-performance major appliances with a healthy buffer – 700 kWh out of 2400 kWh annually for ‘Other Appliances’. A more judicious accounting of appliance loads could reveal savings in this area. The space cooling load could be significantly improved through the use of HRV bypass, natural ventilation (which was not simulated due to complexity), better window shading, and other strategies.

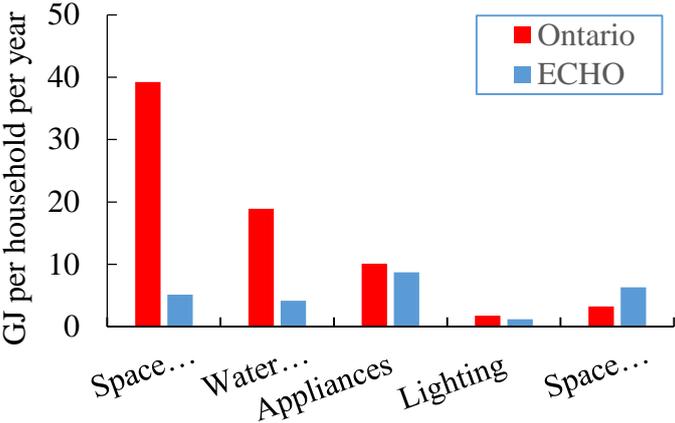


Figure 6: Comparison of annual ECHO loads to scaled Ontario loads

### 5 Measured Competition Performance

This section describes the energy performance of ECHO during the Energy Balance portion of the competition in Irvine, California, from 11 AM October 3 to 11 AM October 11, 2013. The following two figures show energy consumption and production during the contest, with hour 0 indicating the start of October 3. ECHO generated more energy than it consumed, earning full points in the Energy Balance contest.

Figure 7 shows the cumulative energy of ECHO over the course of the Energy Balance contest, with positive values indicating net electrical production. Measurements were made by the competition organizers at the grid tie-in location and by the team through monitoring of each electrical circuit within the house.

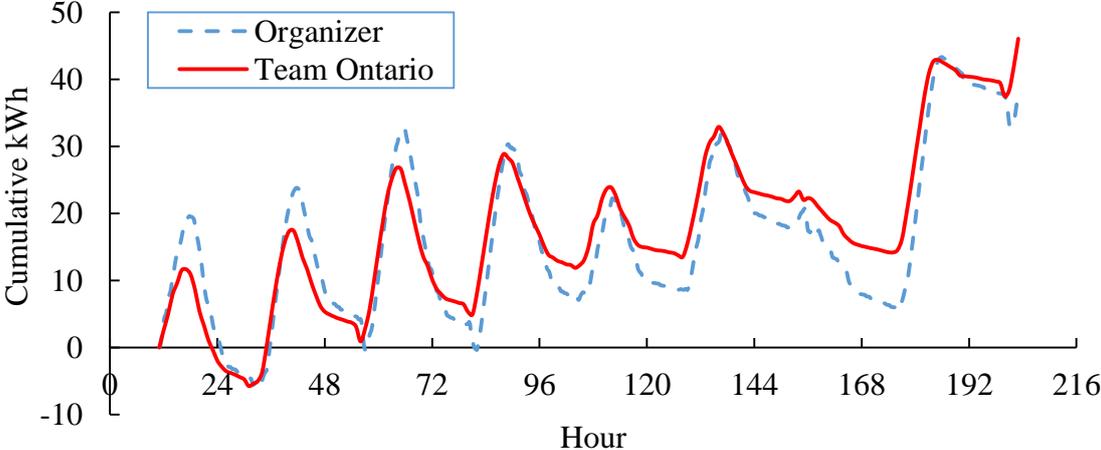
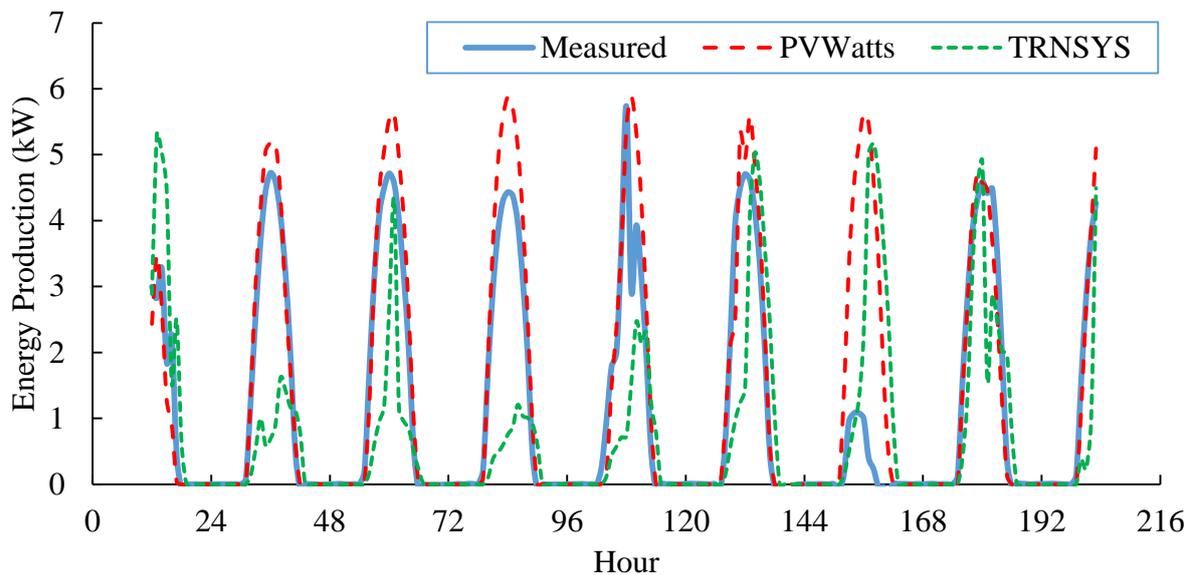


Figure 7: Cumulative energy production and consumption during the competition

Figure 7 indicates a discrepancy between the competition organizer data and Team Ontario’s data. Since the organizers simply measured the net energy flow at the grid tie-in, whereas the team’s measured data was a result of summing measurements of each electrical circuit, it is believed that the team’s measurements are inaccurate. This is likely a result of insufficient system commissioning before shipping the house to California. Although the data are suspect, they may still be useful for a comparison to predicted values.

Figure 8 compares measured PV production from the 7.8 kW crystalline silicon array to predicted values from two simulation tools, PVWatts (National Renewable Energy Laboratory 2012) and TRNSYS 17 (Solar Energy Laboratory 2005). The TRNSYS results are significantly lower than both PVWatts and measured values. This is because three days showed very low production, indicative of overcast skies in the Santa Ana weather file – unusual for California at that time of year – whereas nearby Long Beach, California data were used for PVWatts. This illustrates the difficulty inherent in using specific days from a TMY file for analysis, and highlights the importance of using the same weather data, when possible, for comparison of different simulation tools. Although TMYs are useful for determining the impact of design changes and estimating annual energy consumption, actual meteorological data should be used for validation of the model.



**Figure 8: Comparison of measured and predicted photovoltaic array performance**

Inaccuracies were also observed in the measured PV results. Each of the three circuits (10 panels per circuit, each panel with its own microinverter) had a constant measured production of 133 W at night. To correct this, 133 W was subtracted from each circuit at all time-steps. Unlike some inverters, the model used for ECHO’s array does not draw a ‘parasitic’ load at night.

Further, the measured production is believed to be an underestimate of actual production, as ‘clipping’ was observed around noon on many days of the competition – when the microinverters curtail production to avoid damage. Each microinverter had a rated capacity of 215 W, implying maximum production of 6.45 kW – significantly more than the maximum indicated in Figure 8.

Table 4 indicates the estimated electricity demand and production annually in Ottawa and for the competition in Irvine, along with measured values.

**Table 4: Estimated and measured electricity demand**

End Use	Electricity demand (kWh)		
	Ottawa, Ontario (annual)	Irvine, California (estimated)	Irvine, California (measured)
<b>Lighting</b>	363	17	11
<b>Appliances</b>			
Dishwasher	141	4	7
Clothes washer	110	2	--*
Dryer	480	8	6
Refrigerator	440	9	7
Oven/cooktop	550	17	8
Other	700	19	17
<b>Appliance total</b>	2421	59	45
<b>Space conditioning</b>			
Space heating (heat pump)	1303	0	
Space cooling (heat pump)	2062	102	104**
Pumps and fans	456	20	
<b>Total, space conditioning</b>	3821	122	104
<b>DHW (auxiliary heater)</b>	1153	16	9
<b>Grand total</b>	7758	214	180
<b>PV production</b>	9846	263	219
<b>Surplus</b>	2088	49	39

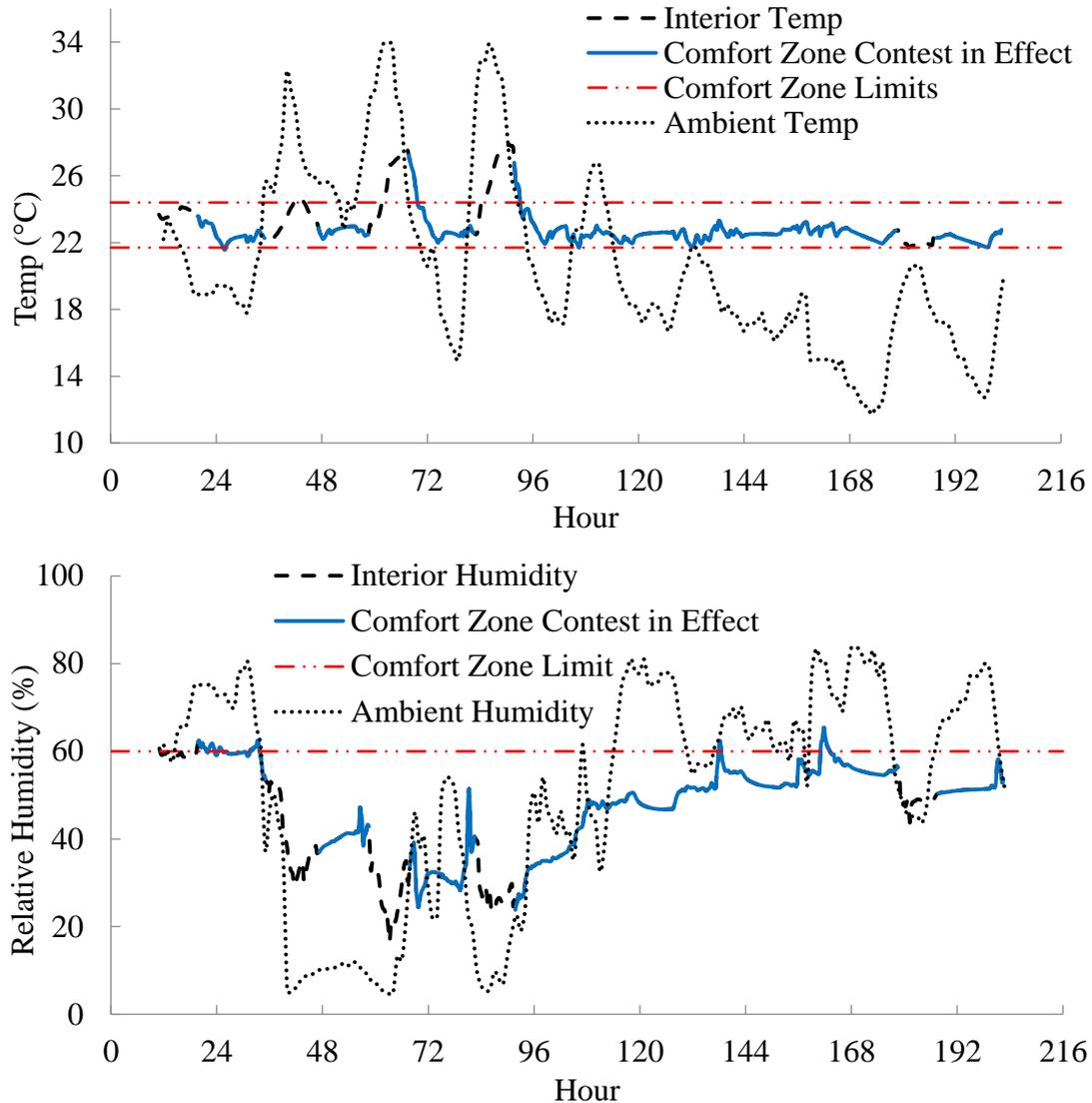
\*The clothes washer energy was not recorded due to an error in the monitoring system.

\*\*Pump and fan energy was not monitored separately from the heat pump.

More problems with monitored energy were observed. A null value was returned for the clothes washer. The cooktop measurements are believed to be off by a factor of 2, and are likely closer to 16 kWh. The space conditioning loads – including the heat pump, circulation pumps, fans in the air handler and heat dissipater, and the ERV – are also believed to underpredict actual consumption.

To summarize, measurements of both energy production and consumption are believed to be underpredicted; these errors largely cancel out, resulting in a final cumulative energy value close to the organizer's measurements. These results indicate that commissioning of monitoring systems should be better coordinated, including allocation of sufficient time in the construction schedule for commissioning. Should ECHO see further use as a research platform, these problems with the monitoring system will need to be corrected.

The Comfort Zone contest specifies that the temperature must remain between 21.7°C and 24.4°C, and relative humidity must stay below 60%, except during public tours (11 AM – 7 PM Thursday - Sunday). Figure 9 compares measurements inside the house to external conditions, which were taken at John Wayne Airport, approximately 12 kilometers from the competition site.



**Figure 9: Comfort Zone contest results**

Overall, the IMS was effective at maintaining interior comfort conditions, even when outdoor temperature dropped quickly or when relative humidity peaked above 60%. The exception was during the half-hour ‘grace period’ after the public exhibit ended for the day. It was not possible for the system to meet ramp rates of 6°C/hour, leading to the loss of several points in the Comfort Zone contest. Fortunately it is unlikely that a ramp rate of this magnitude would be required during normal operation of the home.

## 6 Conclusion and Future Work

This paper has described how building performance simulation aided the design of ECHO, Team Ontario’s entry into the U.S. Department of Energy Solar Decathlon 2013. A building performance simulation student team supported by a faculty advisor was assembled in order to conduct sensitivity studies on key building parameters and provide results to the integrated design team. Photovoltaic simulations for a 7.8 kW crystalline array were also conducted to help ensure energy consumption would be less than production on an annual basis in Ottawa, Ontario, and during the 8-day competition in Irvine, California.

Sensitivity studies were conducted in EnergyPlus; a second model was created in TRNSYS for comparative purposes and to couple the building model directly with the mechanical system model, a two-tank solar-assisted heat pump. Simulated space conditioning loads increased by approximately 60% following this coupling, due to non-ideal behaviour of the system. ECHO is expected to use 25-34% of the energy of a typical Canadian home and generate a surplus of approximately 20% on an annual basis.

Simulated space and water heating requirements were significantly less than average demand in Ontario. Space cooling energy was actually higher than typical for those houses in Ontario with active cooling. An interesting use of ECHO as a research platform would be to investigate operational approaches to reduce the space cooling load, such as free cooling or more effective use of window shading.

Energy flows during the competition were analyzed; however, it is believed that both energy consumption and production were underestimated due to improper monitoring system commissioning. As such, the data are of limited value. Fixing the monitoring system is critical to future in-situ analyses of electricity consumption and demand.

The project helped reduce barriers to the application of building performance simulation in design practice by providing students with applied training and by educating the integrated design team in the benefits of BPS. It contributed to the demonstration component of ECHO, in which thousands of students, industry professionals, and members of the public viewed the home.

Following the competition, ECHO returned to Ontario, where it could be used for further research utilizing BPS. The most important next step is to update the building model with 'as-built' parameters. The model should be further verified by quantifying numerical errors in the calculation, and then, after the monitoring system has been commissioned, validated against measured energy consumption from in-situ operation. This would provide an accurate simulation model for future use of ECHO as a research and testing platform. Another interesting research project would be to create a 'reference model' based on ASHRAE 189.2 or the National Building Code, to quantify more precisely the energy savings compared to typical Canadian housing.

Overall, this project was a success. The BPS team provided valuable input to the integrated design process, including architectural and mechanical aspects of the home. The work contributed to Team Ontario's first place win in the Engineering contest and first place tie in the Energy Balance contest, and provided an opportunity for students to learn practical skills in the field of building performance simulation.

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